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# Flake morphologies and patterns of core configuration at the Abric Romaní rock-shelter: A geometric morphometric approach

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ABSTRACT

The current debate about Mousterian core technologies mainly focuses on the issues of flake predetermination and the morphological similarities of blanks in discoid and centripetal recurrent Levallois methods. To date, the arguments presented have either been based on qualitative analyses of the cores or on the use of ratios of linear measurements to infer the shape of the detached flakes. This paper presents the results of applying 2D geometric morphometric analysis to the flake assemblages in the archaeological collections from the O and M levels of the Abric Romaní rock-shelter and from materials produced by experimental knapping. The results reveal a pattern of core configuration in the Levallois artefacts from level O and a high level of morphological correspondence between the core-edge flake outlines in discoid and Levallois recurrent centripetal technologies. This evidence reinforces the hypothesis that the discoid and the Levallois recurrent centripetal methods share some techno-morphological features. The knappers' ability and the purposes of the reduction sequences play important roles in metrically differentiating between them, otherwise the differences between the two methods would be even smaller. The use of geometric morphometric analysis of flake assemblages can enhance discussions of flaking technologies in lithic studies and quantitatively improve our understanding of the patterns of core configuration and the skills of the prehistoric knappers.



## 1. Introduction

During the Middle Paleolithic, the use of core technologies was generally stable, with a few knapping methods being used over a long period (Boëda et al., 1990; Bourguignon, 1997; Delagnes and Meignen, 2006; Delagnes et al., 2007). Overall, Levallois and discoid technologies were the most heavily used knapping strategies, and in recent decades, the interpretation of their basic features has generated a major debate. The most commonly used descriptions of Levallois and discoid technology were advanced by Boëda (1993, 1994), who identified six discriminating criteria. According to these definitions, discoid technology shares four of the six criteria that define Levallois technology, and only two criteria separate the different methods: the hierarchal relationship between the surfaces, which is present in the Levallois method and is not fundamental in discoid strategy; and the orientation of the fracture plane in comparison with the plane of intersection of the two surfaces, which is secant in discoid and parallel in Levallois (Vaquero, 1999).

Some authors claims that the definitions identified by Boëda (1993, 1994) are too strict when compared with the dynamic processes of the knapping sequence and in particular with the archaeological record, which shows marked changes in how these technologies were applied (Dibble and Bar-Yosef, 1995; Turq, 2000; Slimak, 2003; Vaquero and Carbonell, 2003; Picin et al., 2013). A striking example is a core configuration with secant fracture planes and hierarchization of the flaking surfaces, which is generally referred to as hierarchized centripetal (Vaquero and Carbonell, 2003; Martí et al., 2009). The debate generated by comparing the archaeological collections shone light on the beliefs of those who emphasized the differences between the discoid and Levallois recurrent centripetal technologies (Boëda, 1993; Jaubert and Farizy, 1995; Jaubert and Mourre, 1996; Pasty, 2000), while others proposed to cluster them within the centripetal recurrent group, highlighting their similarities and the possible continuum between

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these two knapping strategies (Lenoir and Turq, 1995; Slimak, 1998; Turq, 2000; Baena Preysler et al., 2003; Vaquero and Carbonell, 2003).

A second aspect of the debate concerns the issue of flake predetermination. In Levallois, predetermination has been associated with the procedure of core configuration in which preparing the lateral and distal convexities gave the knappers a high degree of control over the dimensions of the detached flakes (Geneste, 1985; Boëda, 1994). Although this feature has been documented in experimental knapping and in the archaeological record (Geneste, 1985; Boëda, 1994; Schlanger, 1996; Geneste et al., 1997), some criticisms have been advanced. Noble and Davidson (1996) challenged the idea that Paleolithic knappers intentionally predetermined the Levallois flakes, whereas Bar-Yosef and Van Peer (2009) argued that it was difficult to interpret predetermined and predetermining products without flake refitting. Dibble (1989), in contrast, after comparing various lithic assemblages from western France in which there was no significant metric difference between the Levallois blanks and the other flakes, implied that there had been no predetermination.

The issue of flake predetermination also arises in discoid technology. Some authors claim that the discoid strategy retains a high degree of predetermination, basing their assumptions on the morphologies of certain blanks, such as core-edge removal flakes and pseudo-Levallois points (Boëda, 1993; Locht and Swinnen, 1994; Mourre, 2003). Conversely, others interpret these blanks as the by-products of the reduction sequence used to maintain core convexity (Martí et al., 2009; Vaquero et al., 2012a).

Another aspect related to this issue refers to the fact that the intermediate and final morphologies of discoid and Levallois blanks might be similar because the reduction strategies are recurrent (Ohnuma, 1990; Boëda, 1993). A simple change in the flaking angle of the striking platform, or an invasive detachment, might change the classification of the flake or the core from Levallois to discoid or vice versa (Moncel, 1998; Mourre, 2003). Attributing cores and flakes to one of these technologies should therefore only be determined after a complete examination of the lithic assemblage.

Generally speaking, the shapes of flakes have been broadly associated with the configurations of the core flaking surfaces and with the position of the previous detachments that guide the outlines of the flakes (Inizian et al., 1992; Boëda, 1994; Bar-Yosef and Kuhn, 1999; Van Peer et al., 2010). Managing the number and position of the ridges on the core surface while also controlling platform thickness, might enable the knapper to influence the dimensions and morphologies of the blanks (Van Peer et al., 2010). The striking archaeological example of these features is the Levallois core from Maastricht-Belvédère, known as "Marjorie's core" (Schlanger, 1996). The refitting analysis documented 6 phases of Levallois reduction in which the Neanderthal knapper took advantage of distal and lateral convexities for arranging and predicting the direction of subsequent detachments (Schlanger, 1996). This mental organization of the exploitation of the core yielded nine metrically similar Levallois flakes that were different from the other blanks produced (Schlanger, 1996). Eren and Lycett (2012) pointed out similar results after comparing experimental knapping materials and showing that preferential Levallois flakes exhibited less dimensional variability than the flakes detached during their production.

A recent study, using molded glass cores with different surface morphologies and a mechanical hammer, showed that the sizes and outlines of flakes are influenced considerably more by platform depth and exterior flaking angle rather than core shape (Rezek et al., 2011). Moreover, a 2D geometric morphometric analysis highlighted that flakes from different cores can be virtually similar in dimension and shape, whereas flakes from the same type of core may vary substantially (Rezek et al., 2011). In lithic studies, knapping experiments under strict protocols are important for understanding the basic principles of stone flaking. However, discriminating between technological categories during the experimental analysis is important to understanding the development of reduction sequences and to correlating the results with the archaeological materials. Moreover, classifying the flaking products is critical to comprehending how flake morphologies vary during the reduction sequences.

This paper aims to explore the issues of predetermination and morphological similarities between the centripetal recurrent Levallois and bifacial discoid methods from a 2D geometric morphometric perspective, adding new data to the ongoing debate by using the Hshape software developed by Crampton and Haines (1996). This study aims to understand whether the products that these two technologies intended to produce could be discriminated in different categories of lithic blanks, and whether the technical similarities between reduction methods cause morphologically analogous flakes to be produced.

## 2. Method

The application of geometric morphometric analysis to physical anthropology has attracted several archaeologists to this discipline, and in recent years, an increasing number of publications have applied morphometric concepts and methodologies to archaeological materials (Grosman et al., 2008; Archer and Braun, 2010; Costa, 2010; Bretzke and Conard, 2012; Buchanan et al., 2012; Eren and Lycett, 2012; Lycett and von Cramon-Taubadel, 2013). However, the lack of homologous landmarks on many objects (Bookstein, 1997; Gunz et al., 2005) implies that caution is required when applying these methodologies. Elliptical Fourier Analysis (EFA) is a well-established approach to analyzing the outline shapes of complex object that lack homologous landmarks (Kuhl and Giardina, 1982; Crampton, 1995). The earliest use of EFA in the pioneering works of Gero and Mazzullo (1984) and Saragusti et al. (1998) passed unobserved by the archaeological community, and has only recently been applied, using R language scripts (R Development Core Team, 2010), to various categories of artifacts (Iovita, 2009, 2010, 2011; Iovita and McPherron, 2011; Rezek et al., 2011; Borel et al., 2013). Elliptical Fourier analysis, however, is sensitive to the starting point selected for the outline's coordinates, which could influence the subsequent statistical examination (Haines and Crampton, 2000). This aspect is particularly problematic in morphometric analysis of flake assemblages, in which the high variability of shapes makes it difficult to identify one common starting point for a large number of samples. Crampton and Haines (1996) avoided this problem by using the "Fast Fourier Transform" (FFT) to compute the harmonic spectrum. The FFT does not work directly with the raw xy-coordinates, as in elliptic Fourier shape analysis, but operates on the tangent angle as a function of arc-length connecting the coordinates (Haines and Crampton, 2000). FFT is performed by using the free Hshape software (Web link: http://data.gns.cri.nz/paperdata/paper.jsp?id=78473). This software uses the Hmatch program to allow the selection of the starting point to be circumvented by adjusting the starting positions of the entire population of the outlines studied, and allows for maximum overlap between samples (Haines and Crampton, 2000). This methodology has been extensively applied in paleontology (Schneider et al., 2010; Simon et al., 2011) and may be highly applicable to lithic studies.

The 2D geometric morphometric analyses, referred to in this paper, were carried out using the following free software: tpsDIG2 (Rohlf, 2004) and Hshape (Crampton and Haines, 1996). The latter is composed of three different programs: Hangle, Hmatch and

Hcurve. The ventral surfaces of the flakes, together with a scale in centimeters, were scanned using the Epson Perfection V500 2D scanner. The flakes were orientated with the flaking axes pointing in the same direction. Adobe®Photoshop software was used to convert the images to grey scale. They were then processed using the tpsDIG2 software to calculate 500 xy coordinates of the flake outline. During this step, the area of the flake was also determined. Hangle software was then used to process the tpsDIG2 files. In order to eliminate any pixel noise resulting from the scanning, a smoothing normalization at 96 was run on the outlines, and the shapes were then automatically standardized for size using the perimeter length. In the analysis are considered the first 10 harmonics. The first harmonic has no significance in terms of shape, and was ignored during subsequent statistical analyses (Haines and Crampton, 2000). For each harmonic, two Fourier coefficients were produced. The data was then processed using Hmatch software, which adjusts the starting positions of the entire population of outlines under study, in order to allow maximum overlap. The files were processed using the Hcurve software, which performs an inverse Fourier transform on files of Fourier coefficients and is used to reconstruct files of the xy-coordinates (1024 per contour) of outlines. These files can be used to create synthetic outline shapes and are a great aid in interpreting multivariate statistical data. These xy-coordinates are processed using the PAST free software (Hammer et al., 2001) for Principal Component analyses. The synthetic outline was reconstructed by using the Hangle Fourier option in PAST.

## 3. Material

Geometric morphometric analyses were performed on certain technological categories of discoid and Levallois recurrent centripetal artifacts, taking into account the products of these two knapping methods: Levallois flakes, discoid centripetal flakes, core-edge removal flakes and pseudo-Levallois points. Because the flaking sequences of the archaeological materials may be fragmented, the analyses of materials from levels O and M of the Abric Romaní rock-shelter will be compared with materials produced by experimental knapping. A total number of 791 complete chert flakes were selected for the analysis of both the materials produced by experimental knapping and the lithic assemblages from levels O and M of the Abric Romaní rock-shelter (Table 2). The flakes are discriminated in base of dimensional criterion and are analyzed only those in which the sum of the length and the width is equal or bigger than 4 cm. The blanks chosen had unbroken edges and had not been affected by fractures due to trampling. In the archaeological assemblages, level O is still being studied, and only products from an area of about 20 square meters in the western part of the rock-shelter were selected. In the case of level M the whole assemblage was used. The samples from the experimentally-produced collections cover all the technological categories under consideration.

**Table 1**
Metric attributes (mm) and weight (g) of the chert nodules used for the knapping experiments (D: discoid; LR: Levallois recurrent centripetal).

| | Length | Width | Thickness | Weight |
|---|---|---|---|---|
| D1 | 230 | 210 | 75 | 5020 |
| D2 | 200 | 190 | 140 | 5000 |
| D3 | 150 | 140 | 100 | 2140 |
| D4 | 230 | 120 | 85 | 3030 |
| LR1 | 230 | 185 | 120 | 5000 |
| LR2 | 180 | 160 | 120 | 4030 |
| LR3 | 150 | 150 | 125 | 2690 |
| LR4 | 200 | 190 | 120 | 4050 |

**Table 2**
Raw counts and percentages of the flakes examined for geometric morphometric analysis (the general term "centripetal flakes" is referred to Levallois recurrent centripetal flakes and discoid centripetal flakes).

| | Levallois experimental | | Discoid experimental | | Levallois level O | | Discoid level M | | TOT | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *N* | % | *N* | % | *N* | % | *N* | % | *N* | % |
| Centripetal flakes | 76 | 59.8 | 77 | 61.1 | 75 | 39.7 | 141 | 38.5 | 369 | 45.7 |
| Core-edge flakes | 36 | 28.4 | 39 | 30.9 | 93 | 49.2 | 123 | 33.6 | 291 | 36 |
| Pseudo-Levallois points | 15 | 11.8 | 10 | 8 | 15 | 7.9 | 91 | 24.9 | 131 | 16.2 |
| Total | 127 | 100 | 126 | 100 | 183 | 100 | 355 | 100 | 791 | 100 |

### 3.1. Experimental knapping material

The materials produced by experimental knapping are the results of four Levallois recurrent centripetal and four bifacial discoid cores reductions performed by two expert knappers at the Institut Català de Paleoecologia Humana I Evolució Social (Tarragona, Spain). The two expert knappers have similar knapping skills and are often involved in teaching experimental knapping to students of Rovira I Virgili University (Tarragona, Spain). As the flaking properties of the raw materials play an important role in the number of artifacts produced, a high quality chert from the same geological formation located in Norfolk (UK) was used. The main assumption of the utilization of a foreign raw material, from those used at Abric Romaní, is to test from an ideal perspective the flakes productivity of Levallois recurrent centripetal and bifacial discoid technologies by core unit. The nodules used for the experiments have similar sizes (Table 1) and the absence of impurities or fissures allowed the complete and interrupted reductions of the cores until their exhaustions. During the experiments all the products knapped (flakes, cores, fragments, chips, and chunks) were subsequently collected and analyzed. In this manner the total amounts of products by knapping methods are used as term of comparison for the archaeological series. In this paper, only the total numbers of flakes, classified in the technological categories under examination, are reported (Table 2).

### 3.2. Abric Romaní rock-shelter

Abric Romaní rock-shelter is located near the town of Capellades (Barcelona province, Spain) in the travertine cliff named Cinglera del Capelló at 280 m ASL (Fig. 1). The stratigraphic sequence consists of 15 archaeological levels and has been dated by U-series and radiocarbon methods as between 40 and 70 ka (Bischoff et al., 1988; Vallverdú-Poch et al., 2012) (Fig. 1). Level A is ascribed to the Proto-Aurignacian, whereas levels B–P are associated with the Middle Paleolithic (Vallverdú-Poch et al., 2012). In the archaeological sequence, a technological change has been recorded at level M, with a shift from Levallois recurrent centripetal of level O to bifacial discoid. After level M, the discoid method maintained its pre-eminence as the main flaking strategy in the archaeological horizons until level E, at which a return to the hierarchized technology has been documented. In levels O and M, the most frequently-used raw material is chert, and the other stones selected include limestone and quartz, which are found close to the site (Chacón et al., 2013). Previous studies of the varieties of chert in level J have demonstrated that stones from different outcrops has been utilized, and that the lithological formations of San Martí de Tous (≥12–15 km) and Valldeperes (≥20–25 km) had principally been used, as well as – to a lesser extent – that of Panadella-Montemaneu (≥25–28 km) (Vaquero et al., 2012a,b). In levels O and M, patination

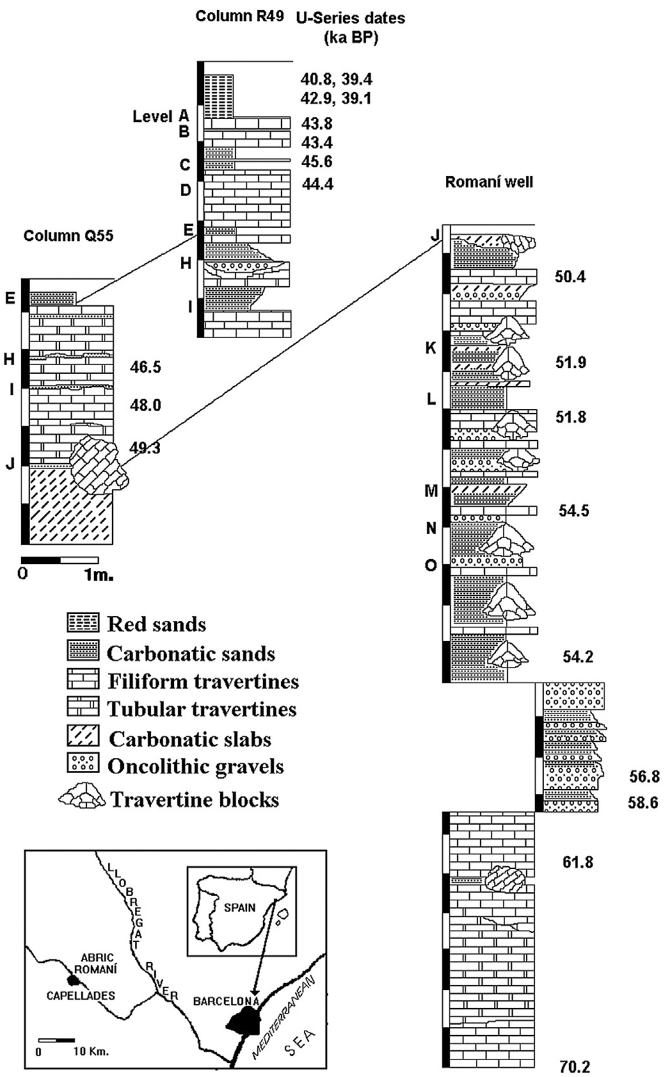


**Fig. 1.** Geographical location and lithostratigraphy of Abric Romaní rock-shelter (Capellades, Barcelona).

considerably affected the surfaces of the flakes, limiting the information available as to the strategies used in procuring them. Macroscopic discrimination of the Panadella-Montemaneu lithological type was less difficult, because the patination turns the raw material light brown, which is very different from the light and dark grey-blues tones of San Martí de Tou and Valldeperes outcrops (Vaquero et al., 2012a).

Level O is dated between 55.0 ± 2.6 and 54.6 ± 2.3 ka BP, and has yielded a copious assemblage of faunal and lithic remains together with wood imprints and combustion structures (Vallverdú et al., 2012; Chacón et al., 2013). Two principal activity areas have been identified in the western part of the rock-shelter. The lithic collection is characterized by the use of the Levallois method in the preferential and centripetal recurrent modes, whereas retouched artefacts comprise denticulates, notched tools and scrapers (Picin et al., 2011; Chacón et al., 2013; Picin, 2014). Zooarchaeological analysis has revealed the presence of red-deer (*Cervus elaphus*), horses (*Equus ferus*) and aurochs (*Bos primigenius*) with some occasional prey species such as rhino (*Stephanorhinus hemitoechus*), wild cat (*Felis silvestris*), hare (*Oryctolagus cuniculus*), bear (*Ursus* sp.) and goat (*Capra aegagrus*) (Gabucio et al., 2012, 2014).

Archaeological level M is dated between 54.9 ± 1.7 and 51.8 ± 1.4 ka and has yielded abundant faunal and lithic remains, wood imprints and combustion structures (Fernández-Laso et al., 2011; Picin, 2014). The taphonomic and zooarchaeological examination identified six main activities areas (Fernández-Laso, 2010). The lithic assemblage is characterized by the discoid bifacial method and a low frequency of denticulate and notched tools (Picin et al., 2011; Chacón et al., 2013; Picin, 2014). The faunal species hunted were principally red-deer, horses and aurochs, and hare, bear and lynx (*Lynx* sp.) were occasionally eaten (Fernández-Laso et al., 2010). Seasonal studies have been performed on the teeth of the herbivores, and these placed the hunts between autumn and early winter (Fernández-Laso et al., 2010).

## 4. Results

The analyses of the morphological variability in flakes produced by centripetal recurrent Levallois and discoid bifacial technology reveal some interesting differences between the experimental and archaeological assemblages. The analysis of the first category of artifacts referred to as centripetal flakes, which include Levallois flakes and discoid centripetal flakes, shows that the outlines of experimental Levallois recurrent centripetal flakes are principally clustered in the positive values of PC1, with morphologies ranging from triangular to irregular, whereas, of the discoid centripetal flakes, a higher number in the sample give negative values of PC1 (Fig. 2, left). The PC1 and PC3 plot, however, shows a greater degree of overlapping of the outlines of flakes produced by the two knapping methods (Fig. 2, right). In the Abric Romaní archaeological material, the PC plot shows a clear differentiation between the level O Levallois recurrent centripetal artifacts and the level M discoid artifacts (Fig. 3, left). Although 3 samples give positive values of PC2, the Levallois artifacts are clustered on the left side of the plot. On the other hand, the centripetal discoid flakes show higher morphological variability, being mostly located in the positive values of PC1 and PC2. This morphological differentiation is even more visible in the plot of PC1 vs. PC3 (Fig. 3, right) in which the majority of the Levallois flakes are grouped between the positive values of PC1 and negative values of PC3 (Fig. 3, right).

The morphometric analysis was also performed on core-edge removal flakes and pseudo-Levallois points. In the experimental series, the core-edge flakes produced by the Levallois recurrent centripetal method show, in the PC1 vs. PC2 plot, great variability in shape, ranging from rectangular to elongated and irregular, with a degree of overlap with the discoid flakes of 69.5% (Fig. 4, left). The discoid core-edge artifacts show morphological variability as well, but the outlines are mostly grouped on the right-hand side of the plot with overlapping of 74.4% (Fig. 4, left). Marked differentiation is present in the PC1 vs. PC3 plot, with the Levallois core-edge flakes mostly grouped in the negative PC1 values, whereas the discoid ones are grouped between the positive values of PC1 and PC3 (Fig. 4, right). In the archaeological materials, a comparison of core-edge removal flakes shows great morphological diversity and overlap between the two methods, although the outlines of level O artifacts are more oriented towards negative values of PC1 (Fig. 5, left). The arrangement of the core-edge morphologies are reversed in the PC1 vs. PC3 plot, with core-edge flakes from level O grouped largely on the positive values of PC1 – ranging between elongated, irregular and rounded morphologies (Fig. 5, right). Level M core-edge artifacts are located in negative PC1 values, with rectangular/irregular outlines (Fig. 5, right).

In experimentally-produced materials, the number of pseudo-Levallois points produced is low (Table 1). The PC1 vs. PC2 plot shows that Levallois outlines are mostly located along the PC1 axis, whereas the discoid pseudo-Levallois points are distributed in

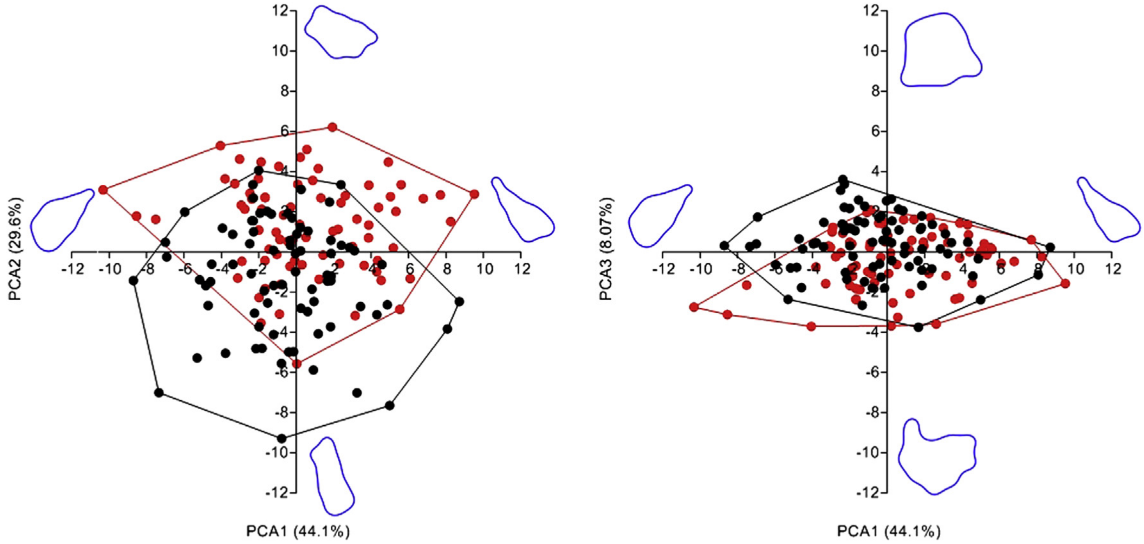


**Fig. 2.** PC plot of experimental Levallois recurrent centripetal (Red) and discoid centripetal flakes (Black). Left: PC1 vs. PC2; Right: PC1 vs. PC3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

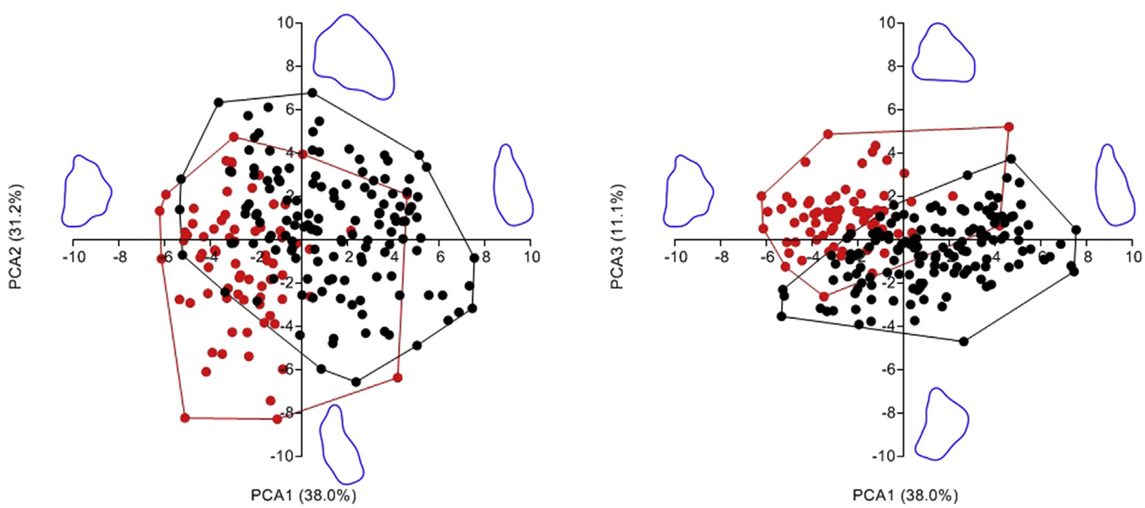


**Fig. 3.** PC plot of Levallois recurrent centripetal of level O (Red) and discoid centripetal flakes of level M (Black). Left: PC1 vs. PC2; Right: PC1 vs. PC3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

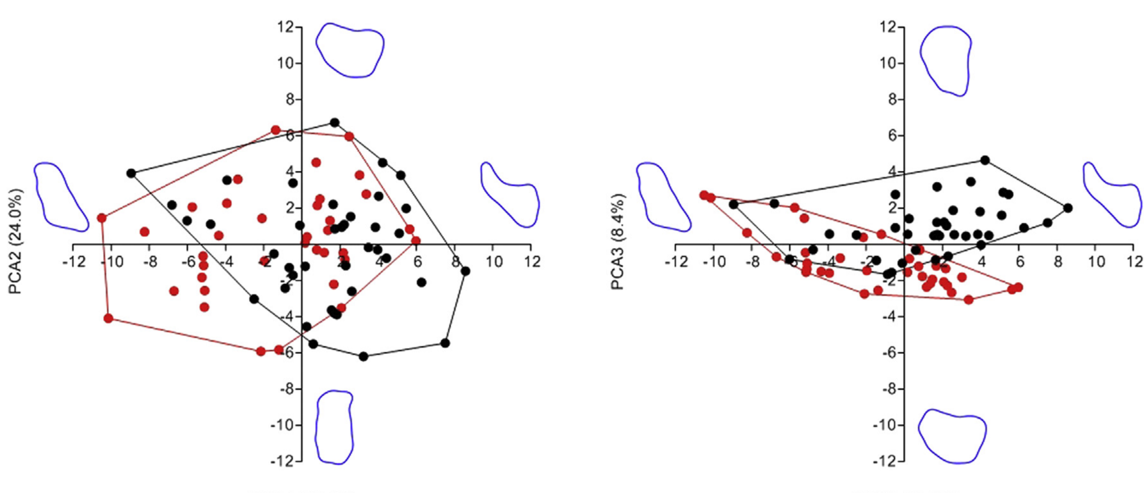


**Fig. 4.** PC plot of experimental core-edge removal flakes in Levallois recurrent centripetal (Red) and discoid bifacial (Black). Left: PC1 vs. PC2; Right: PC1 vs. PC3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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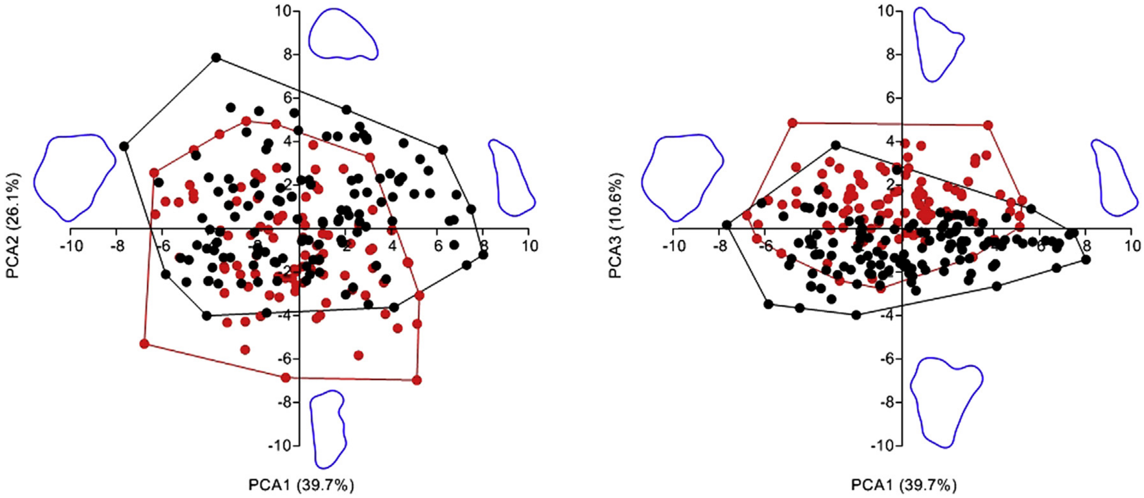


**Fig. 5.** PCA plot of core-edge removal flakes in Levallois recurrent centripetal of level O (Red) and discoid bifacial of level M (Black). Left: PC1 vs. PC2; Right: PC1 vs. PC3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

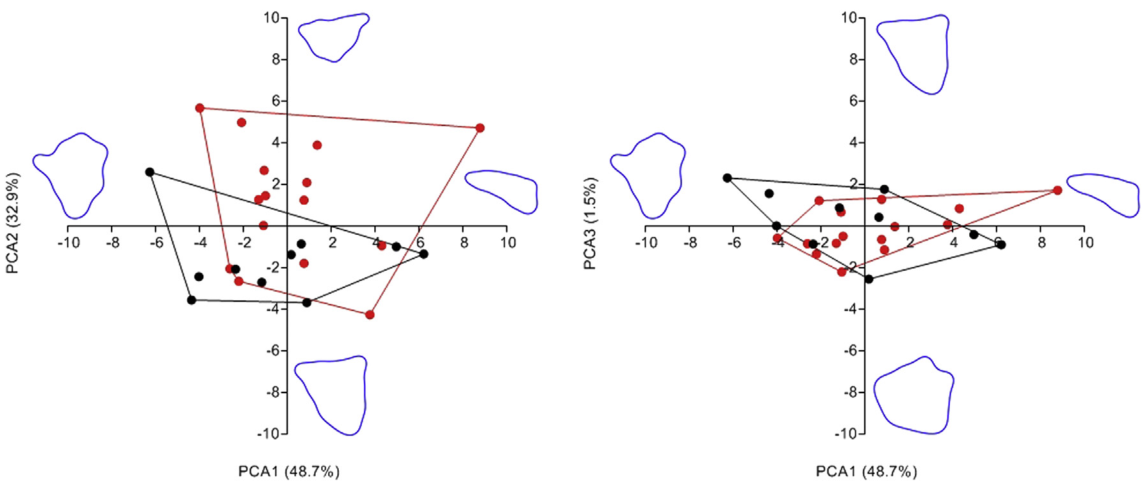


**Fig. 6.** PC plot of experimental pseudo-Levallois points in Levallois recurrent centripetal (Red) and discoid bifacial (Black). Left: PC1 vs. PC2; Right: PC1 vs. PC3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

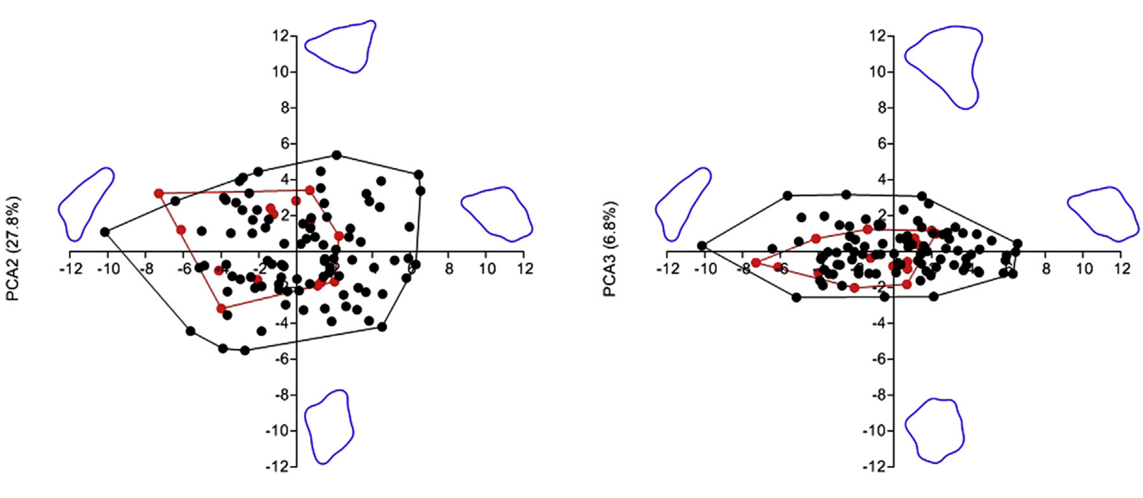


**Fig. 7.** PC plot of pseudo-Levallois points in Levallois recurrent centripetal of level O (Red) and discoid bifacial of level M (Black). Left: PC1 vs. PC2; Right: PC1 vs. PC3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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negative PC1 values (Fig. 6 left). However, in the PC1 vs. PC3 plot, the Levallois artifacts are principally clustered around the area where the two axes intersect, whereas the discoid pseudo-Levallois points are more scattered (Fig. 6 right). In the archaeological collections, there are very few level O pseudo-Levallois points in comparison with level M, and they fall within the morphological variability of the discoid outlines (Fig. 7). The Levallois outlines, however, present different morphologies, as they are not grouped on one side of the plot. On the contrary, level M pseudo-Levallois points show some patterning around the area where the PC1 and PC2 axes intersect (Fig. 7, left). Similarly, the plot of PC1 vs. PC3 indicates analogous characteristics with level O pseudo-Levallois artifacts being more scattered and those from level M more grouped together at the center of the plot (Fig. 7 right).

In order to understand whether the flake shapes were influenced by certain metrical attributes (weight, area and thickness) a General Linear Model test was performed on the artifacts that had been examined using geometric morphometric analysis. In the General Linear Model, the PC1 and PC2 (Fourier descriptor) scores were used as dependent shape variables, and the weight, the area and the thickness of the artifacts were considered to be the independent variables. Table 3 only shows the examples that produced significant results. In the experimental collections, the morphology of centripetal discoid flakes is influenced by area in the PC1 score, while the outlines of core-edge Levallois recurrent centripetal artifacts are influenced by thickness in PC1 (Table 3). In the Abric Romaní archaeological material, the Levallois recurrent centripetal flakes are influenced by weight in the PC1 and by thickness in the PC2 (Table 3).

**Table 3**
General Linear Model using the Fourier descriptors PC1 and PC2 obtained from shape analyses of flakes outlines as dependent variables and weight, area and thickness as covariate. Significant *p* values are bold.

| Flake type | Dependent variable | Source | *F* | *p* |
|---|---|---|---|---|
| Centripetal discoid Experimental | PC1 (Fourier) $R^2 = 0.10$ | Weight | 1.12 | 0.29 |
| | | Area | 5.04 | **0.03** |
| | | Thickness | 1.91 | 0.28 |
| | PC2 (Fourier) $R^2 = 0.016$ | Weight | 0.04 | 0.83 |
| | | Area | 0.06 | 0.80 |
| | | Thickness | 0.92 | 0.34 |
| Core-edge Levallois recurrent centripetal Experimental | PC1 (Fourier) $R^2 = 0.13$ | Weight | 1.16 | 0.28 |
| | | Area | 0.11 | 0.73 |
| | | Thickness | 4.59 | **0.04** |
| | PC2 (Fourier) $R^2 = 0.058$ | Weight | 1.41 | 0.24 |
| | | Area | 1.1 | 0.3 |
| | | Thickness | 1.31 | 0.26 |
| Levallois recurrent centripetal Level O | PC1 (Fourier) $R^2 = 0.07$ | Weight | 4.85 | **0.03** |
| | | Area | 2.28 | 0.13 |
| | | Thickness | 0.40 | 0.53 |
| | PC2 (Fourier) $R^2 = 0.10$ | Weight | 0.64 | 0.43 |
| | | Area | 2.06 | 0.15 |
| | | Thickness | 5.60 | **0.02** |

## 5. Discussion

The geometric morphometric analysis of the products of Levallois recurrent centripetal and bifacial discoid technologies documents a significant pattern of core configurations. In level O, Neanderthals were able to arrange the surfaces of different cores to obtain flakes with a restricted range of morphologies (Fig. 3). This ability was maintained for nodules of different shapes and sizes. Levallois flakes show a different degree of patina and were made from diverse varieties of raw materials, indicating that they were the result of diverse reduction sequences (Picin, 2014). The discrepancy found between these and the experimental data might be related to the different aims of the flaking events. The two expert knappers applied the methods without any particular goals in mind in terms of the morphology of the blanks or economic patterns, merely attempting to be rigorous in applying the method and producing an uninterrupted series of flakes.

On the other hand, the analysis of core-edge removal flakes shows considerable morphological correspondence – in the PC1 vs. PC2 plot – between the two technologies' flake outlines, with no significant differences (Fig. 4, left; Fig. 5, left). There are some variations that are only recorded in the PC1 vs. PC3 plot (Fig. 4, right, Fig. 5, right), which might be related to the different core configurations and ridge distributions. Similarly, the scattering of pseudo-Levallois points in the morphospace reveals great morphological variability, and the few produced during Levallois reduction are included within this group and are not separate from it (Fig. 7). Conversely, the differences in morphologies documented in the experimentally-produced materials could also be related to the different types of core organization (Fig. 6).

The geometric morphometric results emphasize that, when comparing the products of Levallois centripetal recurrent and discoid bifacial technologies, only level O Levallois flakes display some morphological similarity in terms of production. This pattern might be interpreted as a combination of the Neanderthals' expertise and the constraints of core configuration. Paleolithic knappers could predetermine the shape and size of the recurrent flakes by controlling the number and distribution of the ridges on the core surface and the size of the platform (Boëda, 1994; Van Peer et al., 2010). In order to organize core reduction in this way, the knapper would have to display great knapping skill and mastery of the Levallois technology. Because the morphological similarity of level O Levallois flakes is the result of different flake reductions, probably performed by different individuals, this archaeological evidence reveals that the Neanderthal group maintained similar approaches to producing lithic items. This is partially facilitated by the Levallois technology, which is a strict concept in which precise structures must be followed in order to produce Levallois blanks. This accuracy is also observed in the archaeological record, because the way that the lateral and distal convexities were prepared not only influenced the shapes of the flakes, but also reduced the morphological variations between Levallois cores. This feature is common in both African and Eurasian core assemblages which exhibit relative uniformity of the geometric relationship between the margins and the surface morphology of Levallois cores (Lycett and von Cramon-Taubadel, 2013).

The discoid concept, in contrast, is not rigid enough to impose specific core morphologies, and the great variability of discarded cores (unipolar, discoid centripetal and polyhedral) in the discoid context could be the result of discoid flaking sequences (Vaquero et al., 2012a). The use of the discoid method is flexible, and could be applied at any stage of the flaking sequence. This flexibility is also recorded morphologically, because the centripetal flakes detached are not influenced by the way the flaking surface is prepared, but are the result of the knapping stages included in-between the production of core-edge elements.

The morphological variability in the outlines of core-edge removal flakes and pseudo-Levallois points in both technologies implies that it was difficult to control the shape of core-edge blanks. This aspect is even more problematic in discoid reduction because turning the core for the bifacial exploitation makes complicate the preparation and the distribution of the ridges with the aim of predetermining the morphology and the size of the flakes. Detaching these technical pieces is a strategy commonly used in core technologies to maintain convexity (Beyries and Boëda, 1983; Meignen, 1993), and the supposed morphological similarities of some core-edge removal flakes or pseudo-Levallois points might be a redundancy in terms of shape, which has been determined by producing similar core morphologies at certain stages of the reduction (Kuhn, 2010). Furthermore, the experimentally-produced materials provided evidence that the role of pseudo-Levallois points is subordinated to that of core-edge removal flakes, because the limited number (Table 2) indicates that discoid cores could be successfully reduced without detaching these points. On the other hand, the large number of pseudo-Levallois points at level M (Table 2) raises the issue of their intentional production, probably to ensure safe handling during cutting/scraping tasks. These artifacts were produced both at the site and in outdoor flaking sequences, and subsequently transported into the natural shelter as part of the mobile toolkit.

A second aspect highlighted by the geometric morphometric analysis is that flake shape could be influenced by certain variables. The General Linear Model test, performed using the Fourier descriptors as dependent variables, reveals that flake area, weight and thickness could affect the morphology of blanks (Table 3). It is worth noting that the shapes of Levallois flakes of level O are influenced by weight and thickness whereas experimental pieces are affected by area and thickness (Table 3). Conversely, unpaired $t$-test performed on some metric variables (Table 4) indicates that significant means differences are documented between the thickness of Levallois/centripetal flakes ($p \leq 0.0001$, $t = 4.701$, df $= 214$), core-edge removal flakes ($p \leq 0.0001$, $t = 4.351$, df $= 214$) and pseudo-Levallois points ($p = 0.0027$, $t = 3.069$, df $= 104$) of levels O and M. In experimentally-produced materials, although the nodules were similar in size, with the sum of the total weight for Levallois recurrent centripetal artifacts of 15.770 kg and in discoid of 15.190 kg, significant means differences are recorded between area ($p = 0.0151$, $t = 2.488$, df $= 72$) and weight ($p = 0.0215$, $t = 2.351$, df $= 72$) of Levallois recurrent centripetal and discoid core-edge removal flakes.

**Table 4**
Values of mean and standard deviation (*S.D.*) of the variables Area ($cm^2$), Weight (g) and Thickness (cm) in centripetal flakes, core-edge removal flakes and pseudo-Levallois points of experimental materials and archaeological assemblages of level O and M of Abric Romaní.

| | | Area | | Weight | | Thickness | |
|---|---|---|---|---|---|---|---|
| | | Mean | *S.D.* | Mean | *S.D.* | Mean | *S.D.* |
| Centripetal flake | Levallois rec. centr. Experimental | 15 | 10.5 | 17.4 | 20.5 | 8.2 | 4.1 |
| | Discoid Experimental | 12.7 | 7.2 | 14.5 | 13 | 8.5 | 3.3 |
| | Level O | 8.6 | 6.4 | 8.1 | 11.1 | 6.4 | 2.6 |
| | Level M | 8 | 4.5 | 9.6 | 9.1 | 8.5 | 3.4 |
| Core-edge flakes | Levallois rec. centr. Experimental | 21.3 | 15.2 | 41.8 | 48.8 | 12.8 | 6.4 |
| | Discoid Experimental | 14.1 | 9.2 | 21.3 | 22.6 | 10.7 | 5.7 |
| | Level O | 6.6 | 4.8 | 7.4 | 8.8 | 7.5 | 3.2 |
| | Level M | 6.5 | 4.1 | 8.9 | 9.9 | 9.6 | 3.6 |
| Pseudo-Levallois flake | Levallois rec. centr. Experimental | 14.1 | 10.5 | 22.8 | 28.4 | 9.9 | 5.7 |
| | Discoid Experimental | 12.9 | 13.1 | 21.1 | 27.8 | 9.9 | 6.8 |
| | Level O | 7.5 | 4.4 | 7.7 | 6.2 | 7.8 | 2.4 |
| | Level M | 5.9 | 2.8 | 7.3 | 5.2 | 10.6 | 3.3 |

This evidence reinforces the hypothesis that the centripetal recurrent Levallois and discoid concepts share some techno-morphological features (Vaquero and Carbonell, 2003) and indicates that the knappers' ability and the purposes of the reduction sequences play an important role in metrically differentiating between them, otherwise the differences between the two methods would be even smaller. At Abric Romaní, the moderate thickness values of flakes in level O were probably aimed to increase the productivity by core unit whereas in the experimental sequences the modern knappers were not driven by any economic intentions and significant differences are recorded only between pieces used to maintain the core convexity.

The current debate about predetermination and morphological similarities between Levallois and discoid artifacts has either used the ratio of linear measurements to infer the shapes of the flakes detached, or has been based on qualitative analyses of the cores. The use of morphometric analyses on flake assemblages as an alternative technique could quantitatively improve understanding of patterns of core configuration and allow one to postulate about the skills of the prehistoric knappers. From this point of view, the variability within certain lithic assemblages that are claimed to not adhere strictly to the definitions given by Boëda (1994) might be examples of regional or personal variants of Neanderthals' technical behavior. Further studies using morphometric analysis and comparisons with other archaeological assemblages would shine light on this new perspective on hierarchized core technologies.

## 6. Conclusion

The comparison of morphometric analysis of the products of centripetal recurrent Levallois and discoid bifacial technology points to a considerable degree of morphological correspondence, in terms of the flake outlines, between these two methods. The centripetal Levallois flake is the only category of artifacts for which it is possible to determine whether the production of blanks is guided by specific economic strategies, as highlighted by large flake areas and low values for thickness and weight. In the experimentally-produced material and the archaeological assemblage from level M of Abric Romaní, there is no clear morphological pattern for the outlines of the core-edge artifacts. The results provided evidence of a high degree of overlap in terms of shape, and, for the discoid artifacts found at Abric Romaní, the hypothesis of predetermination in producing core-edge removal flakes and pseudo-Levallois points can be rejected.

This study raises the issue of using new quantitative approaches to enhance discussions of flaking strategies in lithic studies. The use of geometric morphometric analysis is an important additional method that could improve our understanding of the issues of predetermination and morphological variability in core technologies by summarizing the information from hundreds of lithic items. The methodology developed by Haines and Crampton (2000), together with the free Hshape software, have significant applicability to lithic studies aimed at investigating regional approaches of Paleolithic knappers to developing core technologies.

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